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Porosity, Surface Area, and Particle Size Effects of CaO Reacting with SO2 at 1100C

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16. ABSTRACT The paper gives results of tests for the reactivity of calcium oxide (CaO) sorbents derived from calcium hydroxide--Ca(OH)2--and calcium carbonate (CaCO3) to gaseous sulfur dioxide (SO2) in a nitrogen atmosphere with a nominal 1100 C, entrained flow reactor and a solids residence time of 0.74 s. The research included direct examination of the combined effect of porosity, particle size, and surface area upon CaO conversion to calcium sulfate (CaSO4). Conversion was inversely related to the 0.20 to 0.35 power of particle size for diameters ranging from 0.77 to 12.1 micrometers. Increased initial surface area from 7 to 62 sq m/g led to higher conversions at all particle sizes, eliminating the possibility of gas film diffusion control. The conversion for both sorbent types is proportional to initial porosity. Substantial expansion of the sorbents during reaction was shown by achieving conversion levels much greater than theoretically possible, given the initial sorbent porosity, the larger-volume product, and an assumed constant particle size. This is contrary to most modeling assumptions, in which the reaction is limited or cut off by pore filling or pore plugging of the sorbent volume.

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a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Pollution Sorbents	Pollution Control	13B 11G
Calcium Oxides	Stationary Sources	07B
Sulfur Dioxide	Surface Area	
Porosity		14G
Particle Size		
Area		12A

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POROSITY, SURFACE AREA, AND PARTICLE SIZE EFFECTS OF CaO REACTING WITH SO_2 AT 1100 °C

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ABSTRACT

Calcium oxide (CaO) sorbents derived from calcium hydroxide [$Ca(OH)_2$] and calcium carbonate ($CaCO_3$) were tested for their reactivity to gaseous sulfur dioxide (SO_2) in a nitrogen atmosphere with a nominal 1100 °C, entrained flow reactor and a solids residence time of 0.74 s. The research allowed for direct examination of the combined effect of porosity, particle size, and surface area upon CaO conversion to calcium sulfate, $CaSO_4$. Conversion was inversely related to the 0.20 to 0.35 power of particle size for diameters ranging from 0.77 to 12.1 μm. Increased initial surface area from 7 to 62 m^2/g led to higher conversions at all particle sizes, eliminating the possibility of gas film diffusion control. The conversion for both sorbent types is proportional to initial porosity. Substantial expansion of the sorbents during reaction was shown by achieving conversion levels much greater than theoretically possible, given the initial sorbent porosity, the larger-volume product, and an assumed constant particle size. This is contrary to most modelling assumptions, in which the reaction is limited or cut off by pore filling or pore plugging of the sorbent volume.

INTRODUCTION

Injection of dry calcium-based sorbents into utility flue gas for removal of SO_2 has prompted extensive studies on process optimization. Improving the economics of the method requires a better understanding of the physical and chemical processes involved in the capture of SO_2 gas by the injected calcium-based solid. While early research (e.g., [1,2]) was primarily done with $CaCO_3$, more recently the focus has been on $Ca(OH)_2$ sorbents (e.g., [3,4]). Commercial hydration of CaO produces fine, powder-like $Ca(OH)_2$ of around 3 μm median diameter at a cost much lower than that of crushing

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and grinding of $CaCO_3$ to a similar size. These $Ca(OH)_2$ sorbents react to greater conversion levels than $CaCO_3$ [5,6], likely due to their finer particle size minimizing SO_2 transfer limitations within the particles. Despite their reactivity advantage, $Ca(OH)_2$ sorbents can pose serious handling and feeding problems due to their extreme propensity to agglomerate.

This tendency to agglomerate has a significant impact upon the ability of the sorbent to capture SO_2. Recent work [7] with $CaCO_3$ and $Ca(OH)_2$ has shown that both sorbent types show substantial increases in conversion as particle and/or agglomerate size decreases. Further, it was shown that particle size was not the sole determinant of reactivity – another factor affected the conversion levels attainable between different sorbents at the same particle size. Past work has shown the importance of surface area [8], porosity [9], and particle size [7] upon the conversion to $CaSO_4$. The objective of this research was to examine the concurrent influence of these variables upon the conversion of CaO [derived from $CaCO_3$ and $Ca(OH)_2$] reacting with SO_2 in an 1100 °C, entrained flow reactor.

EXPERIMENTAL

The reactor system, described more fully elsewhere [10], consists of a graphite element, drop-tube furnace (GFR) capable of operating nominally at 1200 °C or lower in a laminar flow regime. The process gas was composed of 3000 ppm SO_2, 5% oxygen (O_2), and the balance nitrogen (N_2) flowing at a rate of 9 l/min at standard temperature and pressure (STP). The sorbent feeding system entrains particles from a partially fluidized, vibrating sorbent reservoir with a carrier gas flowrate of 0.53 l/min STP. The stainless steel sorbent injector and quartz collection probe are, respectively, water and air cooled. The as-sampled sorbent residence time in the reactor is determined to be 0.74 s from an algorithm developed by Langhaar [11] for solution of the Navier-Stokes equations in the transition region of a straight tube. Solids samples captured by the probe are collected in an inertial cascade impactor which aerodynamically separates particles by size. The temperature and flow conditions of the testing resulted in sampling capabilities over the mass median diameter (MMD) range from 0.44 to 12.1 μm. The reactivity of the samples was determined by analyzing the solids collected on the impactor stages for Ca^{2+} and SO_4^{2-} by atomic absorption spectroscopy and ion chromatography, respectively. Controlled testing showed inaccuracies of +/− 5% conversion when the solids yield of the tray was insufficient. Consequently, data derived from Ca^{2+} yields less than 0.35 mg were not used. This resulted in the virtual exclusion of the last tray (collecting particles 0.44 μm in MMD) from the analysis.

The two sorbents used in this work were produced from Fredonia White limestone ($CaCO_3$) of Fredonia Quarries (Kentucky, U.S.A.). The $CaCO_3$

was aerodynamically sized to a narrow distribution with an MMD of 3.1 μm. This $CaCO_3$ material was one of the materials tested. The $Ca(OH)_2$ was prepared by calcining 3 g batches of the $CaCO_3$ at 980 °C in a nitrogen-swept muffle furnace for 90 min. The calcined material was then slaked at atmospheric pressure with 95 °C water at a molar water/CaO ratio of 18/1 and dried overnight under flowing N_2. Both $CaCO_3$ and $Ca(OH)_2$ were calcined to CaO (termed c-CaO and h-CaO, respectively) in either an isothermal, fixed bed reactor or a muffle furnace prior to injecting into the GFR. Dissimilar conditions (furnace temperatures ranging from 800 to 1000 °C and residence times from 60 s to 6 h) were used to calcine each of the two materials to four desired surface areas due to their different rates of decomposition.

RESULTS AND DISCUSSION

Effect of particle size and surface area

The results presented in Figs. 1a and 1b for h-CaO and c-CaO, respectively, show that particle size has an important effect upon the conversion, X. As particle/agglomerate size decreases, the reaction rate increases, resulting in higher conversion levels for these test conditions (nominal 1100 °C, 3000 ppm SO_2, 0.74 s). The calcined surface area also has an effect upon the reaction: higher initial surface areas lead to increased conversions. The conversion values of h-CaO tend to be higher than those for c-CaO, except for the low surface area and low porosity sample in which they appear coincident.

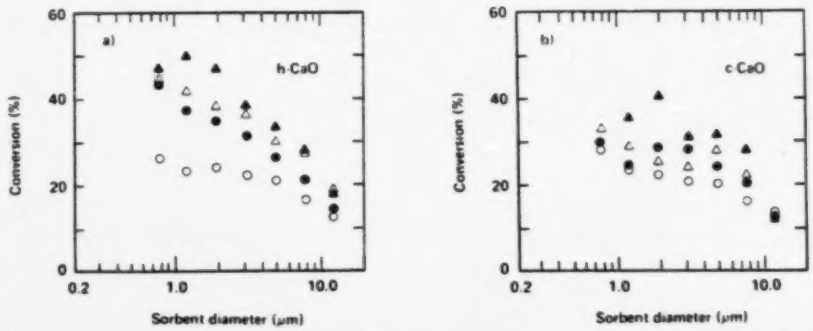

Fig. 1. Effect of particle size and initial surface area upon sorbent conversion at 1100 °C and a residence time of 0.74 s for: (a) h-CaO at initial surface areas of 7 m^2/g (○), 23 m^2/g (●), 42 m^2/g (△), and 62 m^2/g (▲); and (b) c-CaO at 7 m^2/g (○), 33 m^2/g (●), 42 m^2/g (△), and 62 m^2/g (▲).

TABLE 1

Values of n for h-CaO and c-CaO corresponding to Fig. 1. Nominal 1100°C, 0.74 s, 3000 ppm SO_2

Specific surface area (m^2/g)	n value *	
	h-CaO	c-CaO
7	−0.21	−0.21
23	−0.34	NA
33	NA	−0.24
42	−0.27	−0.28
62	−0.33	−0.30

* NA = Not Available.

For even the largest particles considered here, the amount of conversion achieved requires an SO_2 mass transfer rate of less than 2% of the rate expected if gas film diffusion were controlling. This is qualitatively confirmed by the influence of internal surface area upon conversion at constant sorbent diameter (constant external surface area). The exclusion of gas film diffusion as a dominant controlling mechanism suggests that product layer diffusion, chemical kinetics, and pore diffusion mechanisms be considered.

The reaction results can be related to particle diameter, D, by:

$$\frac{X_i}{X_j} = \left(\frac{D_i}{D_j}\right)^n \tag{1}$$

The assumed linear conversion, X, dependency upon the particle size results in an n value which ranges from about −0.20 to −0.35 (Table 1). This is consistent with $CaCO_3$ results of −0.28 to −0.39 [12] and −0.28 [13], and $Ca(OH)_2$ injection results of −0.22 to −0.32 [7].

Theoretical effects of particle size, surface area, and porosity

The relative contribution of particle size, surface area, and porosity to the rate controlling step can be elucidated through examination of the dimensionless Thiele modulus, Φ:

$$\Phi = \frac{R}{3 \times 10^4}\left(\frac{k_v}{D_e}\right)^{1/2} \tag{2}$$

The value of Φ indicates the relative magnitude of the reaction rate (determined by chemical kinetics or product layer diffusion) to the pore diffusion rate. The Thiele modulus can be used to derive the effectiveness factor, η. For mathematical simplicity, a first order, irreversible, isothermal reaction will be assumed for a spherical particle such that:

$$\eta = \frac{1}{\Phi}\left(\frac{1}{\tanh 3\Phi} - \frac{1}{3\Phi}\right) \tag{3}$$

The effectiveness factor represents the extent to which internal surface area participates in the reaction. An effectiveness factor of unity indicates that the reaction occurs uniformly throughout the particle. A value much less than unity indicates significant intraparticle resistance to reactant transfer causing reaction to occur solely at a product/reactant interface.

As seen in eq. 2, the radius, R, is directly proportional to Φ, indicating that increases in the particle size will increase Φ. Diffusion into the particle pores will then be relatively slow compared to the rate of reaction. Thus, the global reaction rate will be limited by the rate of pore diffusion, confining reaction to the outer regions of the particle. It follows that the value of η will be significantly less than unity, indicating that only the outer region of the particle is effective. Conversely, smaller particles are less likely to be diffusion limited and will react throughout more of the particle interior leading to a value of η approaching unity.

The effect of surface area and porosity can be determined by developing the expressions for k_v and D_e in eq. 2. The former is:

$$k_v = 10^4 k_s S_g \rho_{CaO} \tag{4}$$

while the latter is:

$$D_e = \frac{D_c \epsilon}{\tau} \tag{5}$$

The combined diffusivity, D_c, is calculated from the bulk, D_{AB}, and Knudsen, D_K, diffusivities:

$$D_c = \frac{1}{1/D_{AB} + 1/D_K} \tag{6}$$

However, for this small pore size, Knudsen diffusion is controlling the rate of SO_2 movement (D_c is approximately equal to D_K) and the expression for effective diffusivity becomes

$$D_e = \frac{D_K \epsilon}{\tau} \tag{7}$$

The random pore model [14] assumes that:

$$\tau = \frac{1}{\epsilon} \tag{8}$$

So eq. 7 becomes

$$D_e = D_K \epsilon^2 \tag{9}$$

D_K was calculated as in Smith [15] and Bhatia & Perlmutter [16] from:

$$D_K = 9.73 \times 10^{-5} \bar{a} \left(\frac{T}{M_A} \right)^{1/2} \tag{10}$$

where the average pore radius is:

$$\bar{a} = 10^4 \frac{2V_g}{S_g} = 10^4 \frac{2\epsilon}{S_g \rho_{CaO}(1-\epsilon)} \tag{11}$$

making eq. 10:

$$D_K = \alpha \frac{\epsilon}{S_g \rho_{CaO}(1-\epsilon)} \tag{12}$$

where $\alpha = 1.946\ (T/M_A)^{1/2}$.

Substitution of eq. 12 into eq. 9 yields:

$$D_e = \alpha \frac{\epsilon^3}{S_g \rho_{CaO}(1-\epsilon)} \tag{13}$$

and substitution of eqs. 4 and 13 into eq. 2 results in:

$$\Phi = \frac{R}{3 \times 10^2} \left(\frac{k_s S_g^2 (\rho_{CaO})^2 (1-\epsilon)}{\alpha \epsilon^3} \right)^{1/2} \tag{14}$$

Equation 14 shows the anticipated effect of particle size, porosity, and surface area upon the Thiele modulus. Since low Φ moduli result in high values of the effectiveness factor, η, it is clear that small particles, low surface areas, and high porosities will result in higher reaction of the internal area. Conversely, high Φ values are associated with slow rates of diffusion caused by larger particles, higher surface areas, and lower porosities.

The experimentally determined values of S_0 and ϵ_0 (shown in Fig. 2) were used to calculate their effect upon Φ through use of eq. 14. This was done by holding variables fixed, defining

$$\Phi' = \left(\frac{S_0^2 (1-\epsilon_0)}{\epsilon_0} \right)^{1/2} \tag{15}$$

and plotting Φ' against initial surface area (Fig. 3) and initial porosity (Fig.

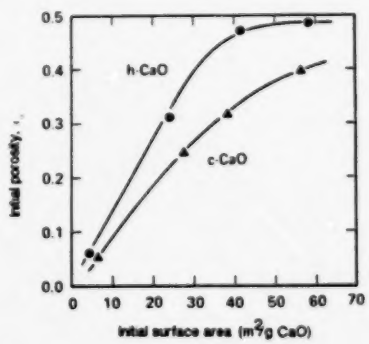

Fig. 2. Relationship between initial porosity and surface area for h-CaO (●) and c-CaO (▲).

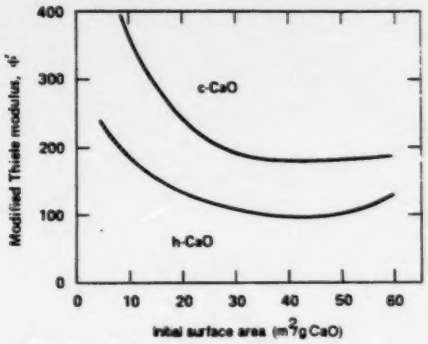

Fig. 3. The effect of initial surface area on the modified Thiele modulus for h-CaO and c-CaO.

4). For the sorbents of this work, it is clear that intermediate surface areas (30 to 50 m^2/g) and porosities (0.3 to 0.4) should have the lowest Thiele moduli, or the higher rates of pore diffusion. Lower Φ values are associated with higher values of η, meaning that more of the sorbent's area is reacting at a rate defined by the exterior surface temperature and reactant concentration. This represents the optimal tradeoff between high surface area leading to increased reaction rate and increased porosity leading to faster reactant pore diffusion. This also helps explain why previous work [4] with high surface area sorbents (80 m^2/g) produced by alcohol hydration had only marginal improvement in sulfur capture.

The higher conversions of the h-CaO over c-CaO at similar particle sizes and surface areas are reconciled with this analysis by the higher porosity of the h-CaO. All other factors being equal, the greater porosity decreases Φ (or Φ') leading to higher effectiveness (η closer to unity) of the interior

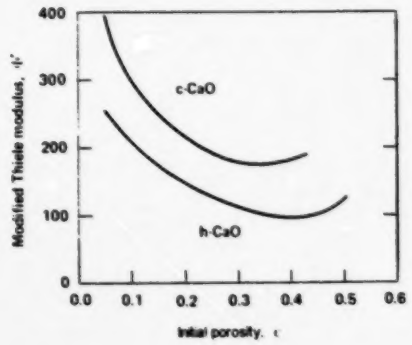

Fig. 4. The effect of initial sorbent porosity on the modified Thiele modulus for h-CaO and c-CaO.

reaction. However, the conversions of the c-CaO and h-CaO at low S_0 and ϵ_0 are similar despite large differences in Φ' (caused, in part, by analytical limitations). It is most likely that, for these materials, gaseous pore diffusion rapidly becomes irrelevant (and similarly, the Φ' concept) as formation of the large $CaSO_4$ product plugs or fills the pores. In this case, the sulfation mechanism would be controlled by diffusion through a product layer.

Several caveats are necessary concerning this interpretation. First, the S_0/ϵ_0 relationship seen in Fig. 2 is not fixed, but rather is a function of the methods of sorbent calcination. Thus, the forms of Figs. 3 and 4 will change for the conditions of each experiment. Further, the S_0 and ϵ_0 values will vary throughout the reaction, changing the Thiele modulus and (potentially) the rate controlling mechanism. Lastly, the relative position of c-CaO with respect to h-CaO is, again, a function of the sorbent preparation conditions. In fact, some commercially available $Ca(OH)_2$ may result in an h-CaO porosity below that of c-CaO, leading to lower Φ values.

The effect of porosity and surface area

The role of initial surface area and porosity is examined in Figs. 5 and 6, respectively. For particle sizes of 1 and 5 μm, conversion values were calculated for each surface area from a linear regression of the X vs. sorbent diameter data (Fig. 1). These values are plotted against initial surface area for both sorbent types in Fig. 5. For Fig. 6, values are plotted for 1, 5, and 10 μm against porosity.

Figure 5 shows the strong influence of precalcine surface area upon the conversion for both h-CaO and c-CaO. For a given surface area, h-CaO reaches higher conversion levels than c-CaO except for the low area, sintered

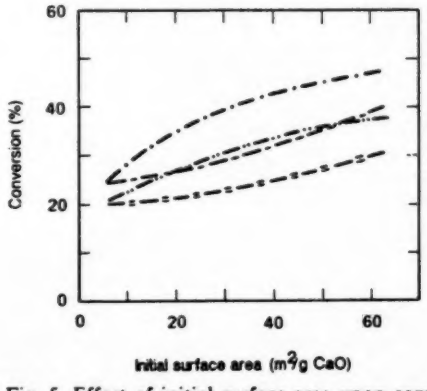

Fig. 5. Effect of initial surface area upon conversion for h-CaO at 1 μm (–·–·) and 5 μm (–··–··) and for c-CaO at 1 μm (——·) and 5 μm (— = — =).

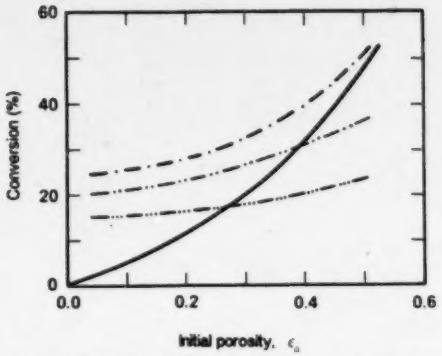

Fig. 6. Effect of initial porosity upon conversion for both h-CaO and c-CaO at 1 μm (–·–·), 5 μm (–··–··), and 10 μm (–···–···) versus the theoretical conversion/pore volume relationship (———).

particles. The data of Fig. 6 indicate that the level of conversion is strongly dependent upon calcined porosity independent of CaO source. This result, when considered with that of Fig. 5, suggests that the higher conversion levels obtained by h-CaO over those of c-CaO at given surface areas for this research (Figs. 1a and 1b) are due to greater pore volume delaying the product layer formation and subsequent pore blockage.

Extrapolation of the 1 μm curve of Fig. 6 to zero porosity illustrates the surprising result that, as porosity approaches zero for a particle approaching the limit of zero particle size, a conversion level of about 20% can be expected. If this extrapolation holds true, it suggests that a mechanism of rapid product layer diffusion is responsible for the high degree of reaction in these very low porosity particles.

The maximum amount of conversion expected for a particle of constant size losing pore volume due to formation of the larger volume product can be determined from [16]:

$$X_s = \frac{\epsilon_0}{(Z-1)(1-\epsilon_0)} \tag{16}$$

This conversion/pore volume relationship is shown as the solid line on Fig. 6. Comparison with the experimental data of this research shows that considerably more reaction occurs at lower porosities than predicted by others based upon pore filling [17]. The experimental conversions exceed the theoretical limits imposed by the initial porosities in a systematic manner; at low porosities both small and large particles react more than predicted, while at higher porosities only the small particles exceed this value, the larger particles apparently showing greater limitations due to pure blockage. As porosity increases toward the theoretical maximum (49% for h-CaO and 54% for c-CaO [18]), the increase of the data over the theoretical values

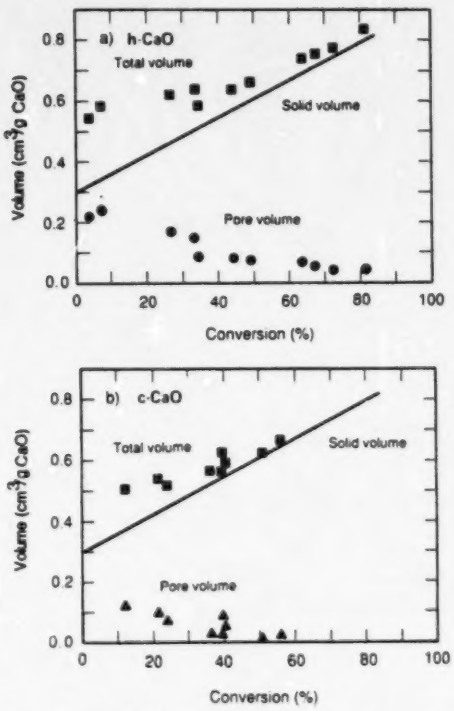

Fig. 7. Effect of reaction upon pore volume for a) h-CaO (●) and b) c-CaO (▲) versus theoretical solid volume (——) and total particle volume (■).

declines. This indicates that substantial particle expansion has occurred for all of the sorbents tested, although the effect is greater at lower porosities. This is contrary to prior expectations that particles retain their original gross external volume [9]. Of the models developed for the CaO/SO_2 reaction (e.g., [6,19,20]), none account for conversions exceeding the theoretical limits imposed by the initial porosity [21]. Kocaefe et al. [21] concluded that sulfation models must incorporate whole particle changes in the mechanism. The evidence here for sorbent expansion and reaction beyond the limits imposed by the original volume is supported by work of Borgwardt&Bruce [8] which illustrates sorbent conversion up to 90% for essentially non-porous ($\epsilon_0 = 0.028$) c-CaO.

Particle expansion throughout reaction was verified with pore volume measurements by mercury porosimetry methods. Figures 7a and 7b show normalized pore, solid, and total volume for h-CaO and c-CaO, respectively. The pore volume was determined experimentally by mercury intrusion methods, the solid volume was calculated from the conversion values, and the total volume is the sum of both. The data show residual porosity at the

point of theoretical maximum conversion (especially for h-CaO) and particle expansion with conversion by the increasing total volume. This supports similar work by Borgwardt and Harvey [2], although for their much larger particles (250 μm), they did not find expansion until the X_s value was reached.

The high conversions for essentially non-porous particles and the conversion values exceeding those expected due to pore volume filling suggest the strong influence of a product layer diffusion mechanism accompanied by substantial particle expansion.

CONCLUSION

The effect of decreasing sorbent size from 12.1 to 0.77 μm is to more than double the conversion values. The order effect of particle size upon conversion ($-0.2 \leq n \leq -0.35$) is consistent with results from other work. The declining conversion values for lower initial surface area sorbents at given particle diameters preclude the possibility of gas film diffusion control.

Analysis of a modified Thiele modulus shows that small particles with low surface areas and high porosities will have the least pore diffusion limitations upon the reaction rate. When the experimentally determined porosities and surface areas for the sorbents of this work were used to calculate the modified Thiele modulus, intermediate surface areas (30 to 50 m^2/g) and porosities (0.3 to 0.4) were found to provide the optimum characteristics for limiting pore diffusion resistance of the reaction rate. These low Φ' values suggest high effectiveness factors, in which the interior surface reacts as if it were exposed to the temperature and concentration conditions of the exterior surface. However, since the relationship between surface area and porosity is not fixed, these optimums can vary depending upon the sorbent calcination conditions.

Although initial porosity is important to reactivity, extrapolation from results shows that a non-porous particle around 1 μm in diameter will reach a conversion of about 20%. This, along with the fact that conversion levels are reached far beyond those predicted by simple product-filling of the initial porosity, suggests that diffusion through the product layer is a necessary mechanism for the reaction conditions of this experiment.

NOTATION

$\bar{a}$ average pore radius, Å
D particle diameter, μm
D_{AB} bulk diffusivity, cm^2/s
D_c combined diffusivity, cm^2/s

D_e effective diffusivity, cm^2/s
D_K Knudsen diffusivity, cm^2/s
i, j respective particle sizes, unitless
k_s rate constant per unit CaO surface area, cm/s
k_v rate constant per unit CaO volume, 1/s
M_A molecular weight of SO_2, g/g-mol
n exponent defined in eq. 1, unitless
R radius at particle surface, μm
S_g specific surface area per unit weight of CaO, m^2/g
S_o initial specific surface area per unit weight of CaO, m^2/g
T temperature, K
V_g pore volume per unit weight of CaO, cm^3/g
X conversion of CaO to $CaSO_4$, %
X_s conversion at complete pore closure, %
Z molar volume ratio of $CaSO_4$ to CaO, unitless

Greek letters

α defined in eq. 12
Φ Thiele modulus defined in eq. 2, unitless
Φ' Modified Thiele modulus defined in eq. 15
ϵ porosity, unitless
ϵ_0 initial porosity of CaO, unitless
η effectiveness factor defined in eq. 3, unitless
ρ_{CaO} true CaO density, g/cm^3
τ tortuosity, unitless

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REFERENCES

1 R.W. Coutant, R. Simon, B. Campbell and R.E. Barrett, EPA Report APTD 0802 (NTIS PB204-385), U.S. Environmental Protection Agency, Industrial Environmental Research Laboratory (presently Air and Energy Engineering Research Laboratory), Research Triangle Park, NC, October 1971.

2 R.H. Borgwardt and R.D. Harvey, Environ. Sci. Technol., 6 (1972) 350.
3 B.J. Overmoe, J.M. McCarthy, S.L. Chen, W.R. Seeker and D.W. Pershing, EPA-600/7-86-040 (NTIS PB87-129250), November 1986.
4 J.P. Gooch, E.B. Dismukes, R. Beittel, J.L. Thompson and S.L. Rakes, Proceedings: 1986 Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_x Control Technologies, Vol. 1, U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, EPA-600/9-86-029a (NTIS PB87-120465), 1986, p. 11-1.
5 R. Beittel, J.P. Gooch, E.B. Dismukes and L.J. Muzio, Proceedings: First Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_2 Control Technologies, Vol. 1, U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, EPA-600/9-85-020a (NTIS PB85-232353), 1985, p. 16-1.
6 J.A. Cole, J.C. Kramlich, W.R. Seeker, G.D. Silcox, G.H. Newton, D.J. Harrison and D.W. Pershing, Proceedings: 1986 Joint Symposium on Dry SO_2 and Simultaneous SO_2/NO_2 Control Technologies, Vol. 1, U.S. Environmental Protection Agency, Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, EPA-600/9-86-029a (NTIS PB87-120465), 1986, 16-1.
7 B.K. Gullett and J.A. Blom, React. Solids, 3 (1987) 337.
8 R.H. Borgwardt and K.R. Bruce, A.I.Ch.E. J., 32 (1986) 239.
9 M. Hartman, J. Pata and R.W. Coughlin, Ind. Eng. Chem. Process Des. Dev., 17 (1978) 411.
10 B.K. Gullett, G.C. Snow, J.A. Blom and D.A. Kirchgessner, Rev. Sci. Instrum., 57 (1986) 2599.
11 H.L. Langhaar, J. Appl. Mech., 64 (1942) A55.
12 M.J. Snow, Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, 1985.
13 Y. Ishihara, C. Asakawa and H. Fukuzawa, Nenryo Kyokaishi (J. Fuel Soc. Jpn), 54 (1975) 175.
14 N. Wakao and J.M. Smith, Chem. Eng. Sci., 17 (1962) 825.
15 J.M. Smith, Chemical Engineering Kinetics, 3rd. ed., McGraw-Hill, New York, 1981.
16 S.K. Bhatia and D.D. Perlmutter, A.I.Ch.E. J., 27 (1981) 226.
17 M. Hartman and R.W. Coughlin, Ind. Eng. Chem. Process Des. Dev., 13 (1974) 248.
18 R.H. Borgwardt, K.R. Bruce and J. Blake, Ind. Eng. Chem. Res., 26 (1987) 1993.
19 P.G. Christman and T.F. Edgar, A.I.Ch.E. J., 29 (1983) 388.
20 P.A. Ramachandran and J.M. Smith, Chem. Eng. J., 14 (1977) 137.
21 D. Kocaefe, D. Karman and F.R. Steward, A.I.Ch.E. J., 33 (1987) 1835.